

Neutrino Colliders

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arXiv:0708.0160 [hep-ex]

Aspen 2008 winter conference

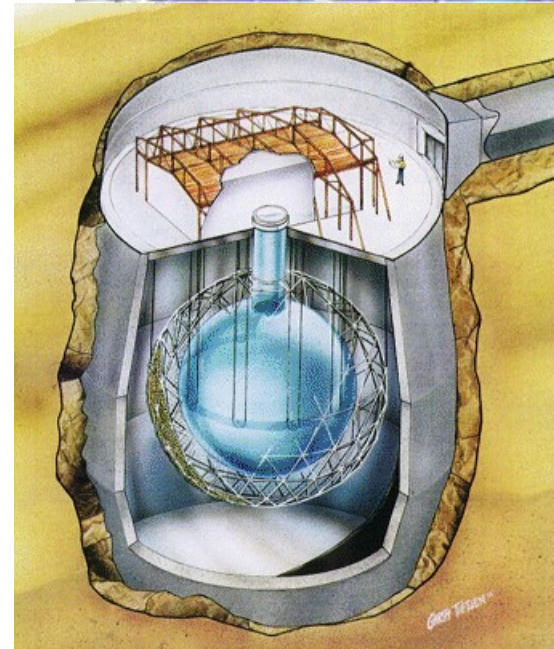
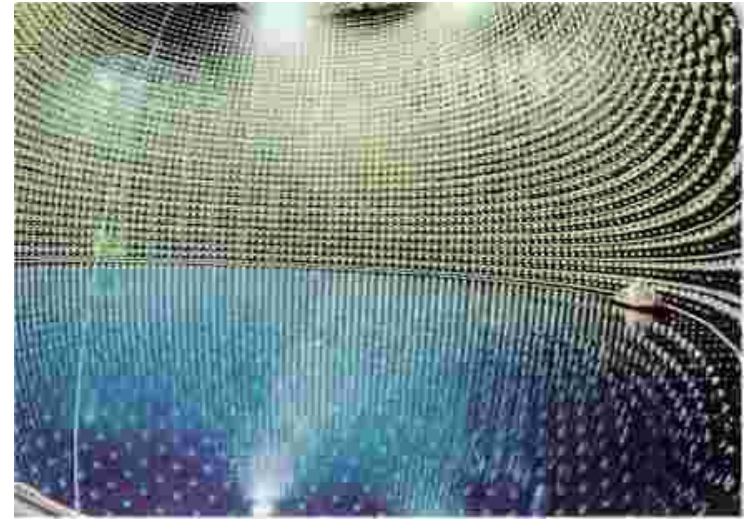
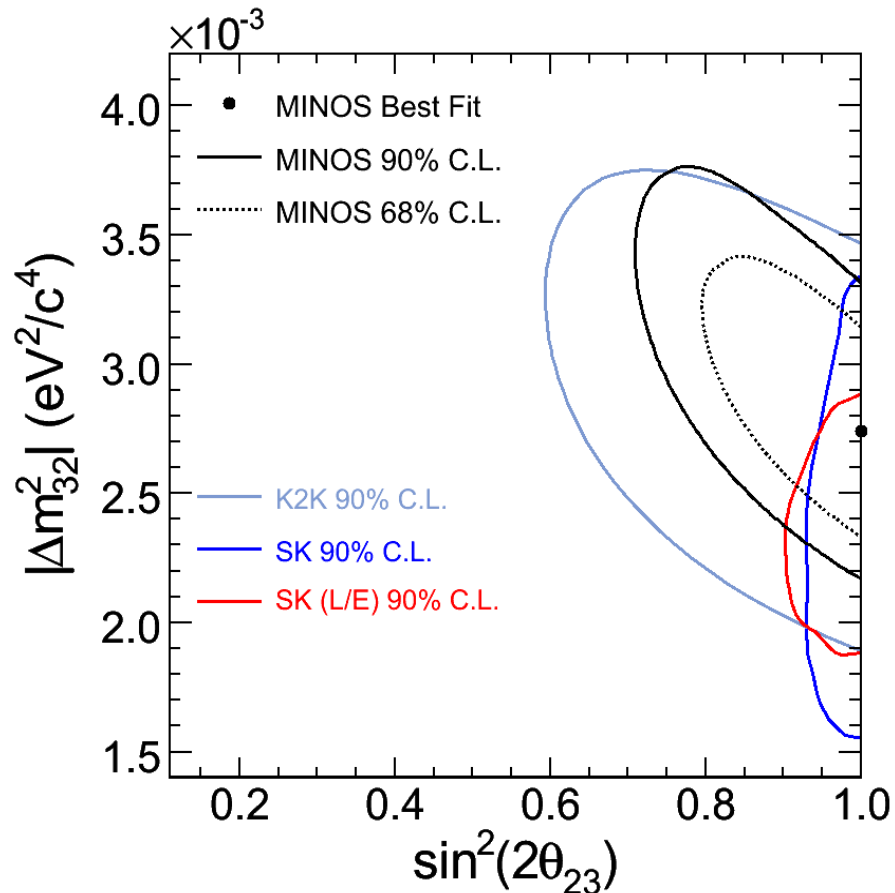
Outline

- Introduction
- Colliding neutrinos with other particles
- Neutrino collider configurations
- Cross sections
- Conclusions

Neutrino beam calculation with BMPT
Cross section calculation with Madgraph

Current neutrino experiments

- Recently established non-zero neutrino mass and neutrino flavor oscillations
- Current experimental goals:
 - Measure parameters (angles, Δm)
 - Identify favored models indirectly



Neutrino physics

- Experiments currently probe mass mixing matrix
 - Questions:
Parameters of mixing matrix
CP-violation in neutrino-sector?
 - Maybe in the future also Majorana vs Dirac nature
- But: for other particles, we are currently exploring the mass generation mechanism. Why not for neutrinos?
- 2 main questions:
 - Origin of mass?
 - Nature of right-handed neutrinos?

- Current or planned neutrino experiments do not directly address the origin of neutrino mass

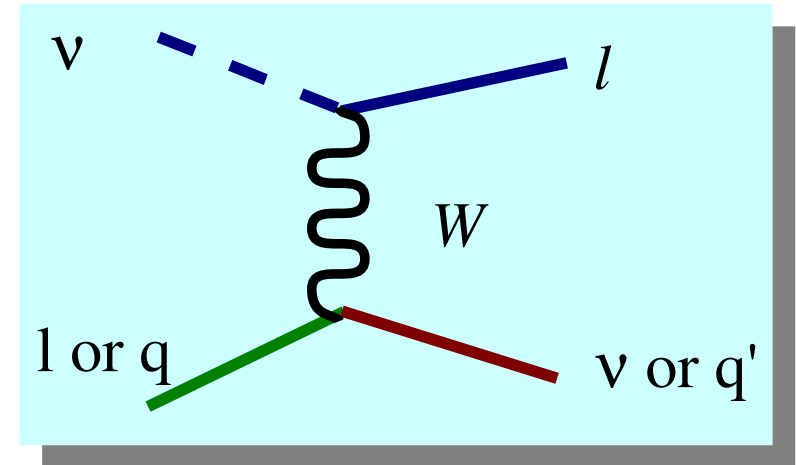
Origin of neutrino mass

- Neutrino mass
 - right-handed neutrinos exist
 - there must be neutrino interactions beyond SM
 - with other beyond-SM particles
 - Can we produce and observe the right-handed neutrino or other possible non-SM particles coupling to neutrinos?
- Higher order symmetries lead to W and Z bosons
 - If they couple to right-handed neutrinos, we might be able to produce them
- Popular theory: see-saw mechanism
 - Right-handed neutrino m_{RH} is heavy
 - At the GUT scale in most theories, but not necessarily
 - Current experimental limits $m_{RH} > 100$ GeV
- Many other possibilities: sterile neutrinos, 4th generation, singlets, more Higgses, and many additional particles

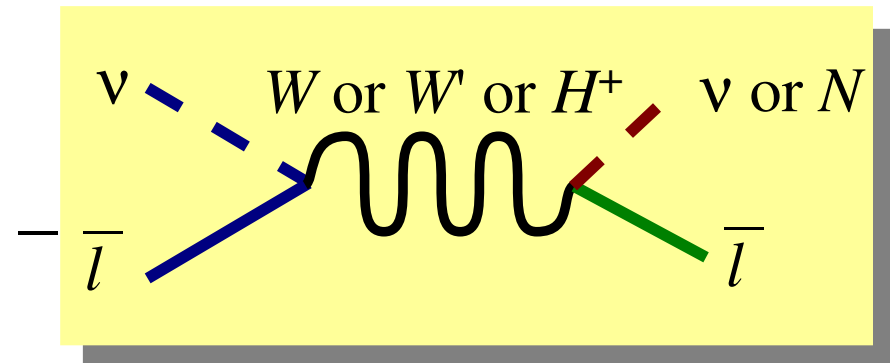
$$m_\nu = \frac{m_D^2}{m_{RH}}$$

Neutrino interactions at high energy

- t-channel W boson exchange
 - also Z boson exchange

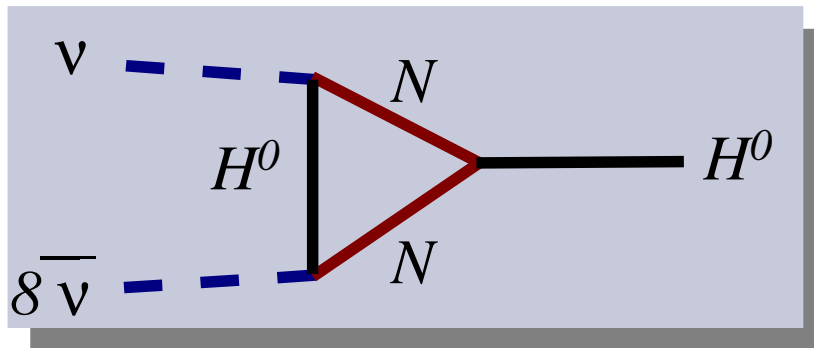
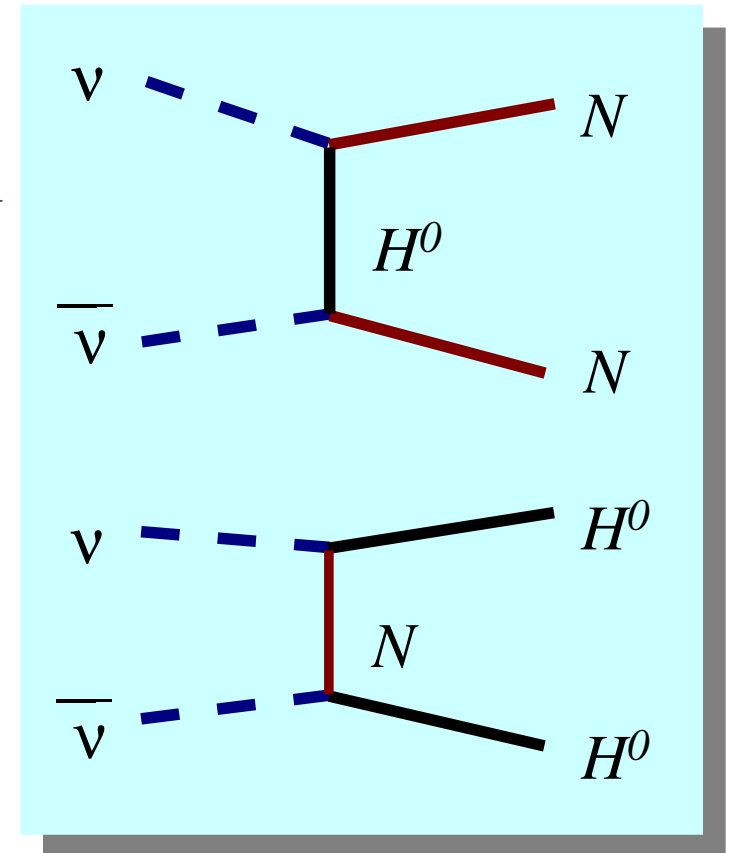
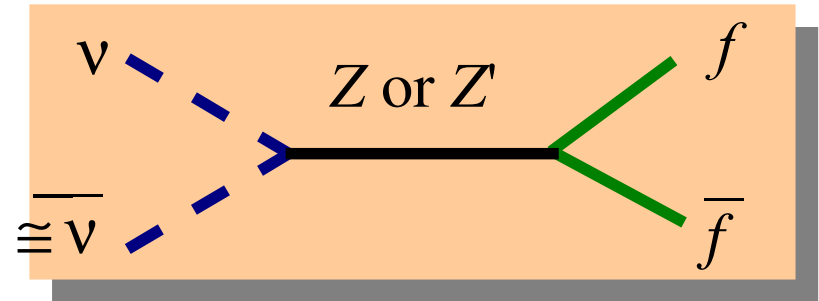


- s-channel W boson production
 - Sensitive to new heavy boson W' or charged Higgs
 - Or other new new particle coupling to neutrino and lepton
 - Possible new particle might decay to other new particles



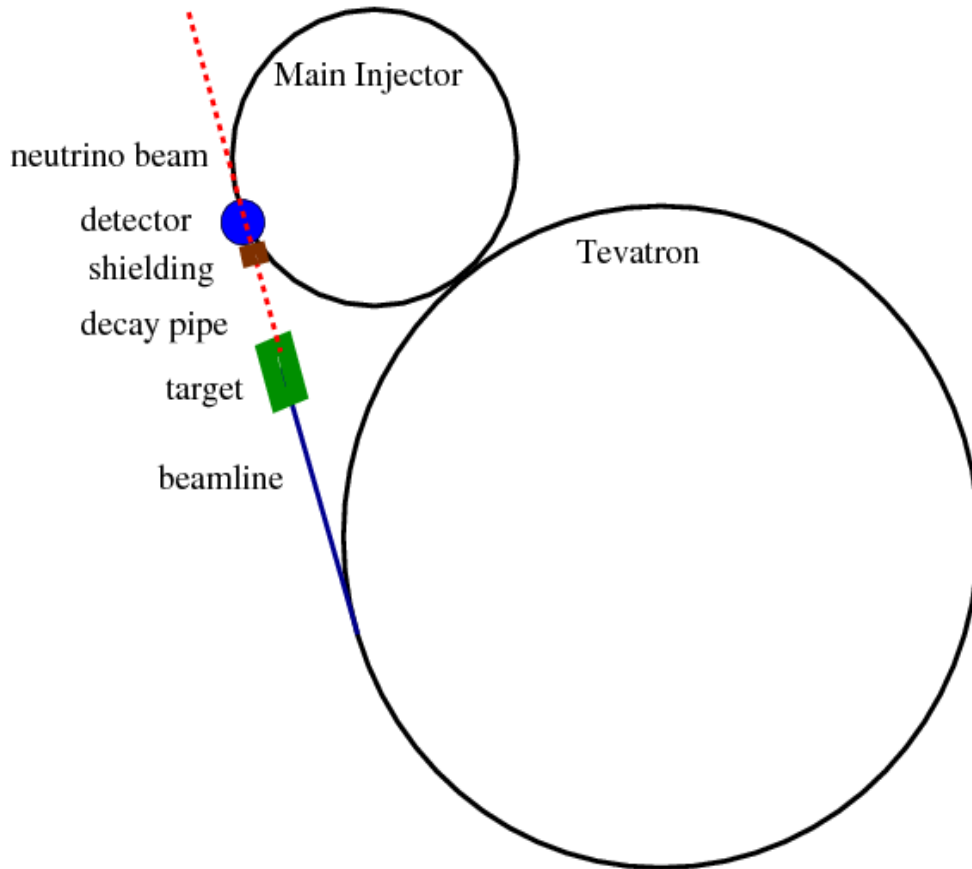
Neutrino-neutrino collisions

- SM: Z-boson production
- New heavy boson Z'
- Pair-production of right-handed heavy neutrinos N – or neutrino-Higgs H^0
- Neutrino-Higgs production via Majorana neutrinos



Neutrino-proton collider

- Fermilab: neutrinos from the Tevatron on protons from the main injector (or the other way around)
- Cern: neutrinos from the LHC on protons from the SPS

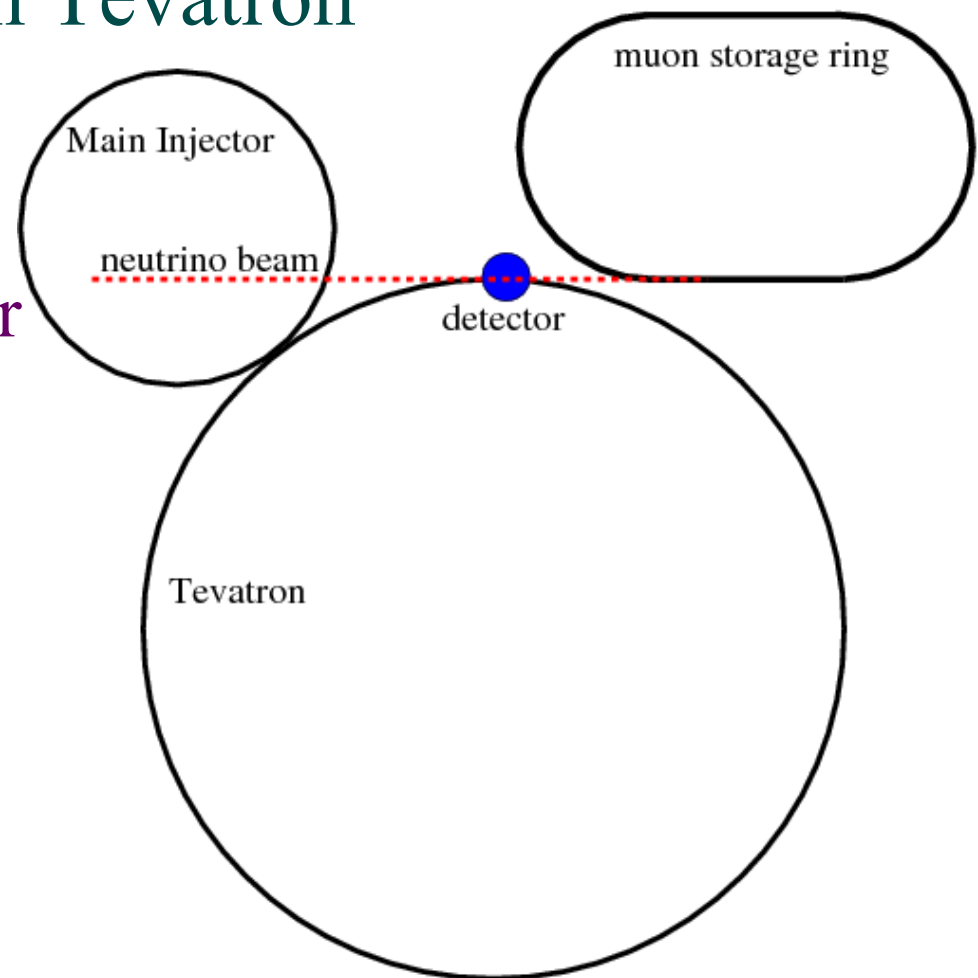


- Assume MI can deliver 10^{14} protons per bunch and 5×10^7 bunches per year
 - similar to “Project X”
- Results in neutrino-proton luminosity of 0.02 nb^{-1} per year
- Neutrino-proton cross section:
 - 1.5 nb at the Tevatron
 - 7.5 nb at the LHC – SPS
- Need factor ~ 100 higher proton intensity just to get started



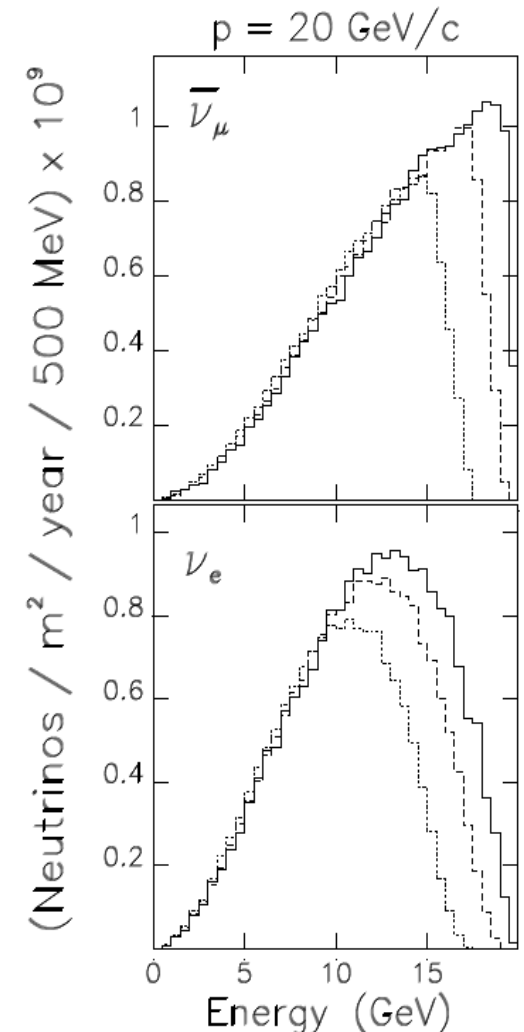
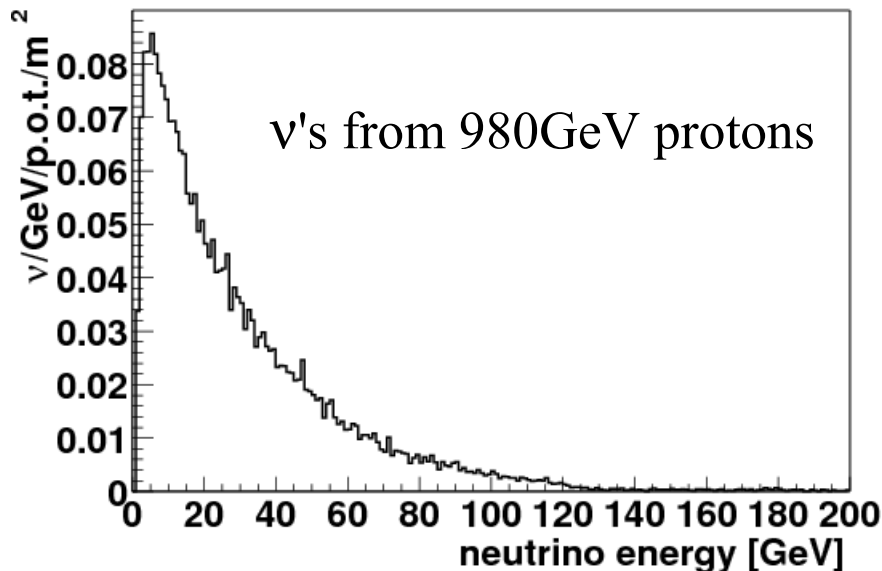
Neutrino factory based neutrino-proton collider

- Neutrino beam from muon storage ring
 - With current muon storage ring design:
0.1 muons/proton, 0.1 neutrinos/muon
- Directed at proton beam in Tevatron (10^{14} protons/bunch)
 - 40 nb^{-1} luminosity
 - 60 SM interactions per year
 - Increase in protons/bunch
 $\times 10$ yields luminosity
comparable to Hera startup



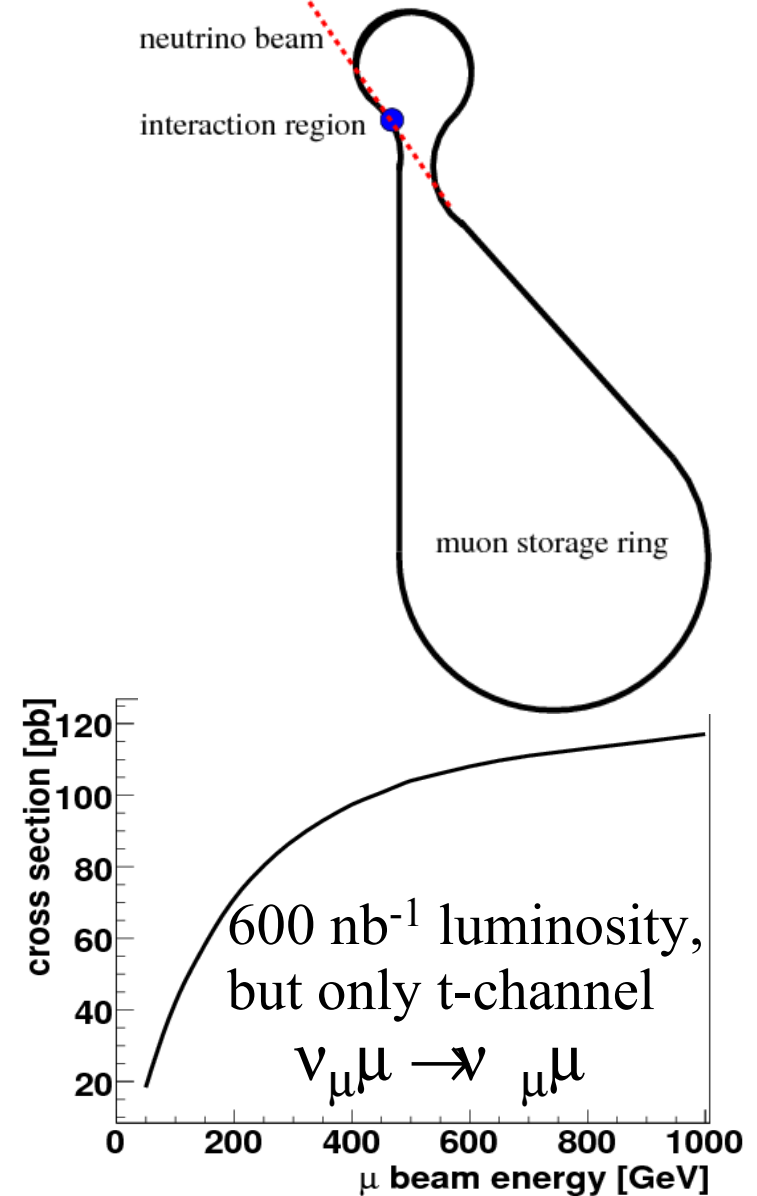
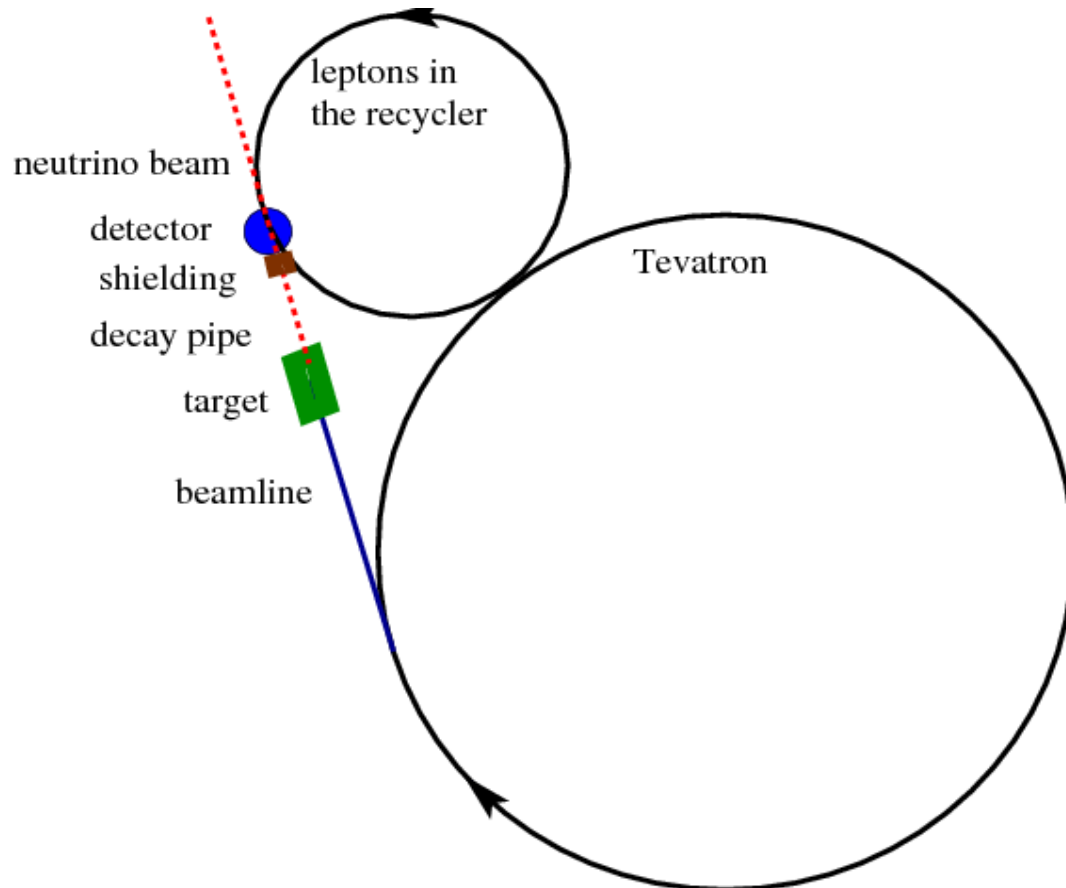
Neutrino production at accelerators

- Only production mode realized so far:
high-energy proton beam incident on target produces pion beam, pion decays lead to neutrino beam
 - broad spectrum, low energy
- Neutrino factory: neutrino beams from muon storage rings
 - high energy ν 's, many ν 's per proton on target

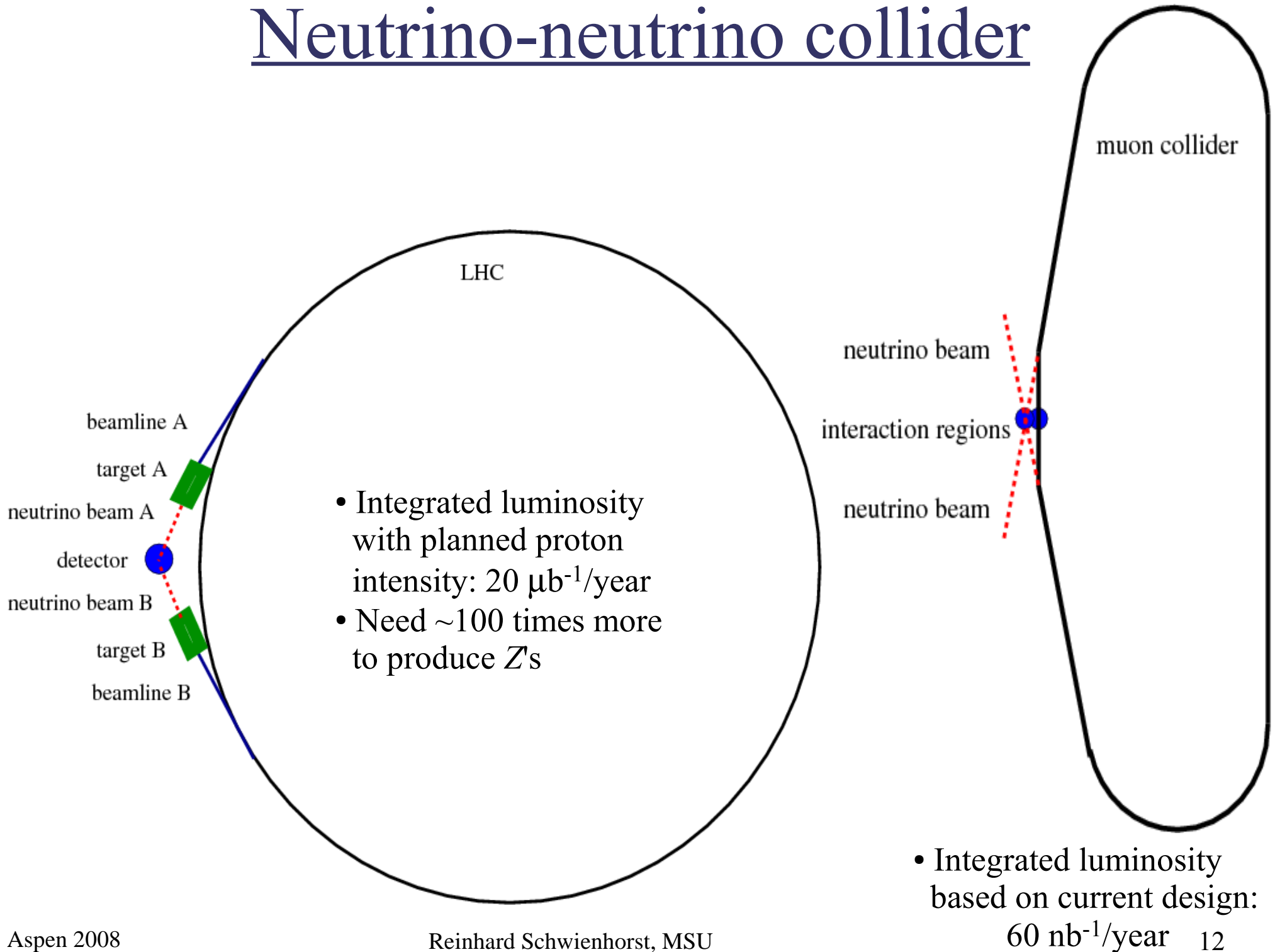


Neutrino-lepton collider

- Neutrinos from the Tevatron, electrons or muons in the Recycler
 - Requires 7 orders of magnitude higher beam intensities than LEP to reach $\sim \text{pb}^{-1}$ luminosity
- Muon storage ring

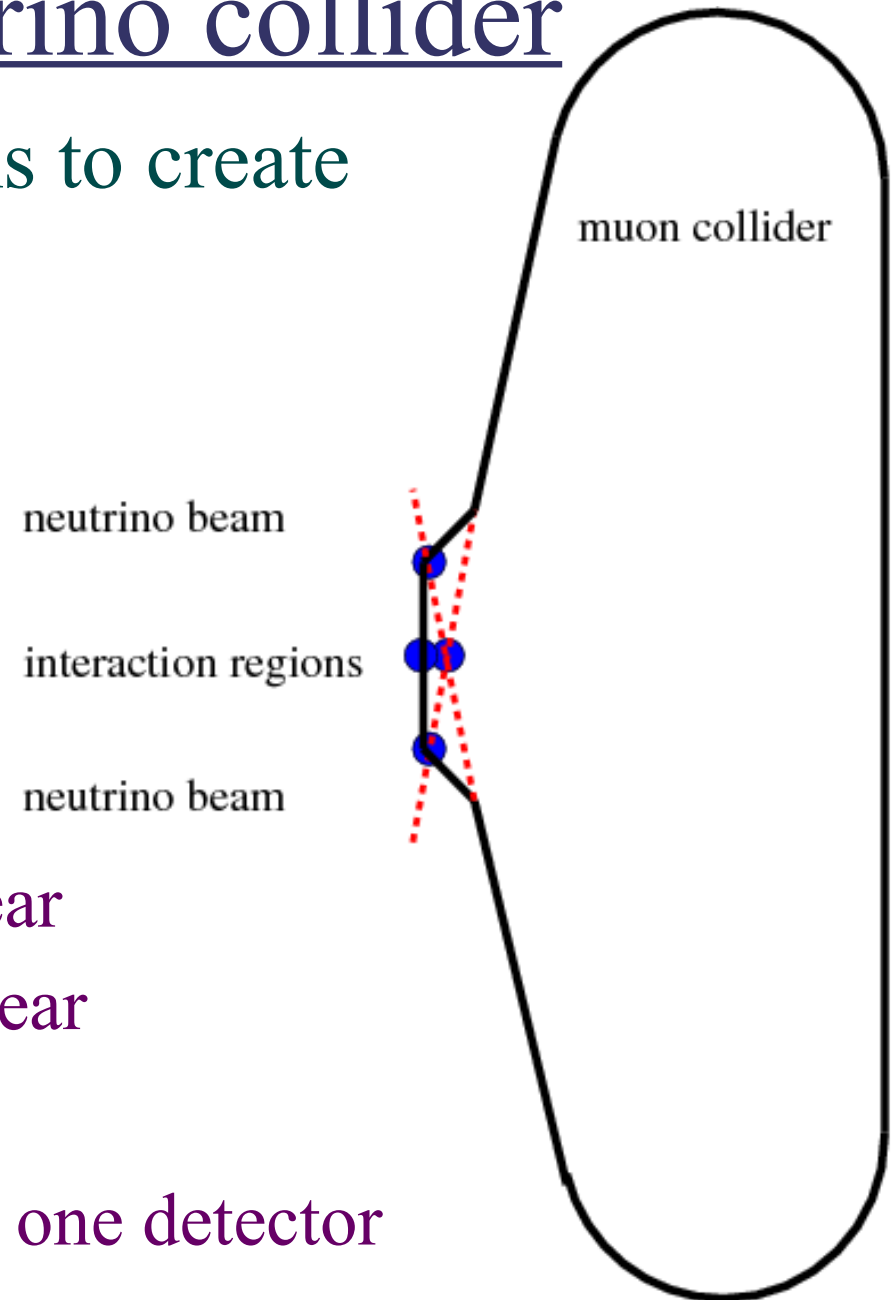


Neutrino-neutrino collider



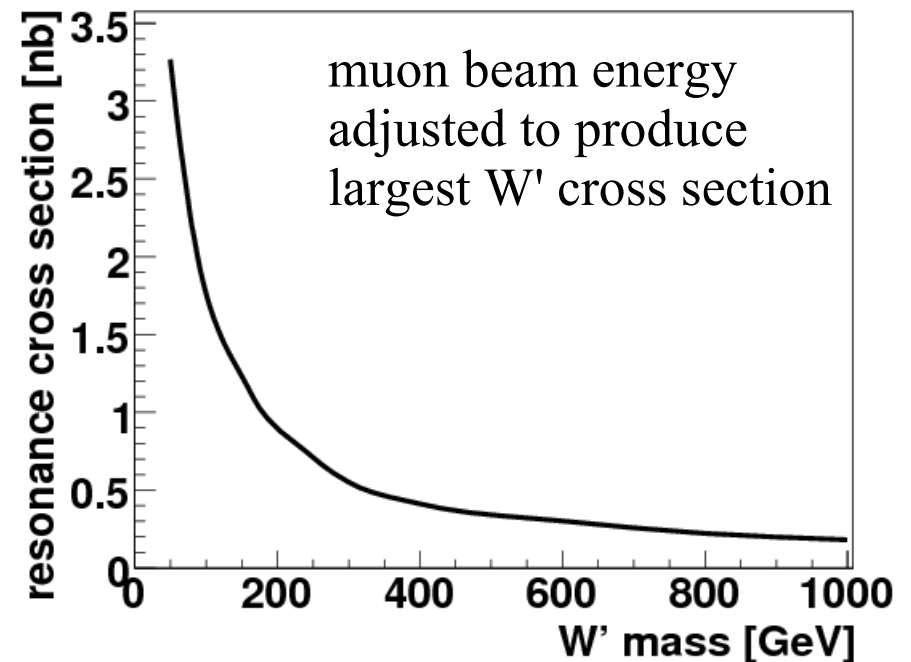
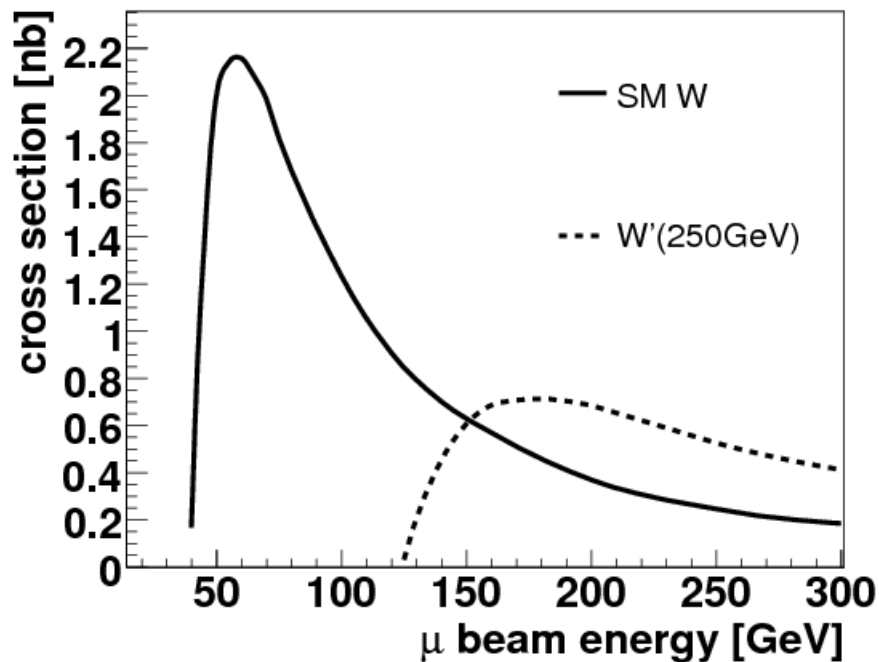
Integrated lepton-lepton, neutrino-lepton, and neutrino-neutrino collider

- Configure muon collider beams to create 4 interaction regions
 - Muon – anti-muon
 - Neutrino – anti-neutrino
 - Neutrino – anti-muon
 - Anti-neutrino – muon
- Luminosity:
 - Neutrino-lepton: 600 nb^{-1} per year
 - Neutrino-neutrino: 60 nb^{-1} per year
- Several detectors
 - Or several interaction regions in one detector



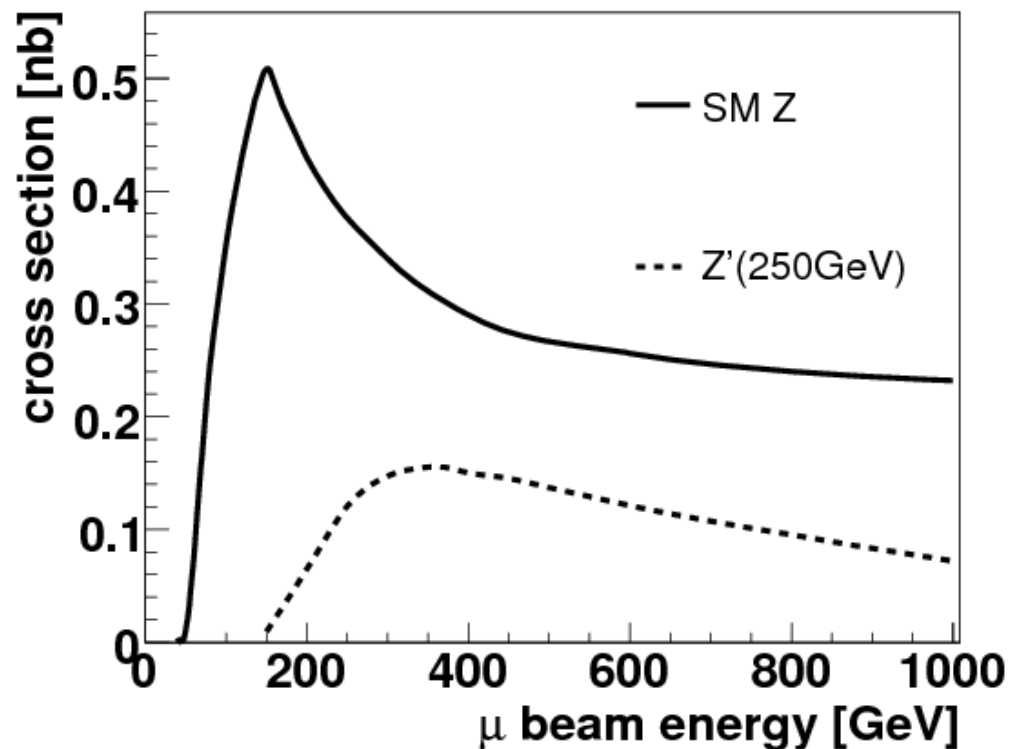
W boson production in a neutrino-lepton collider

- In a neutrino-lepton collider, the W boson is produced in neutrino-lepton annihilation
- With sufficient energy, other heavy objects can also be produced. Example: heavy boson W'
- Large cross sections due to resonance production



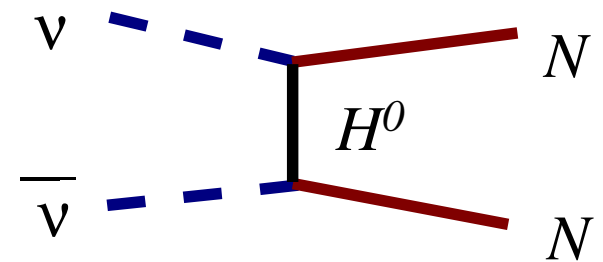
Neutrino collider based on muon storage ring

- SM Z cross section large
 - Neutrino-neutrino collisions will occur in a muon collider, whether we want it or not
 - 30 events per year with current muon collider design
- Sensitive to Z' that couples only to neutrinos

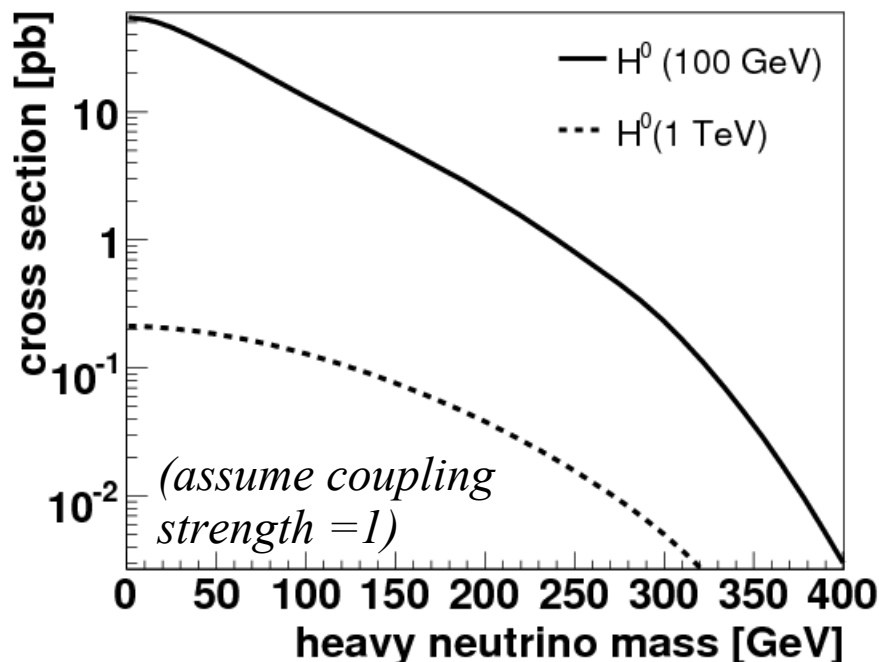


Heavy neutrino production

- Heavy right-handed neutrino production through coupling to neutrino-Higgs (H^0)



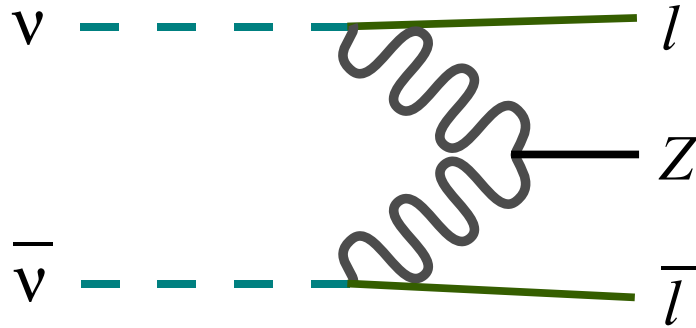
N pair production at a neutrino collider
based on 1 TeV muon collider



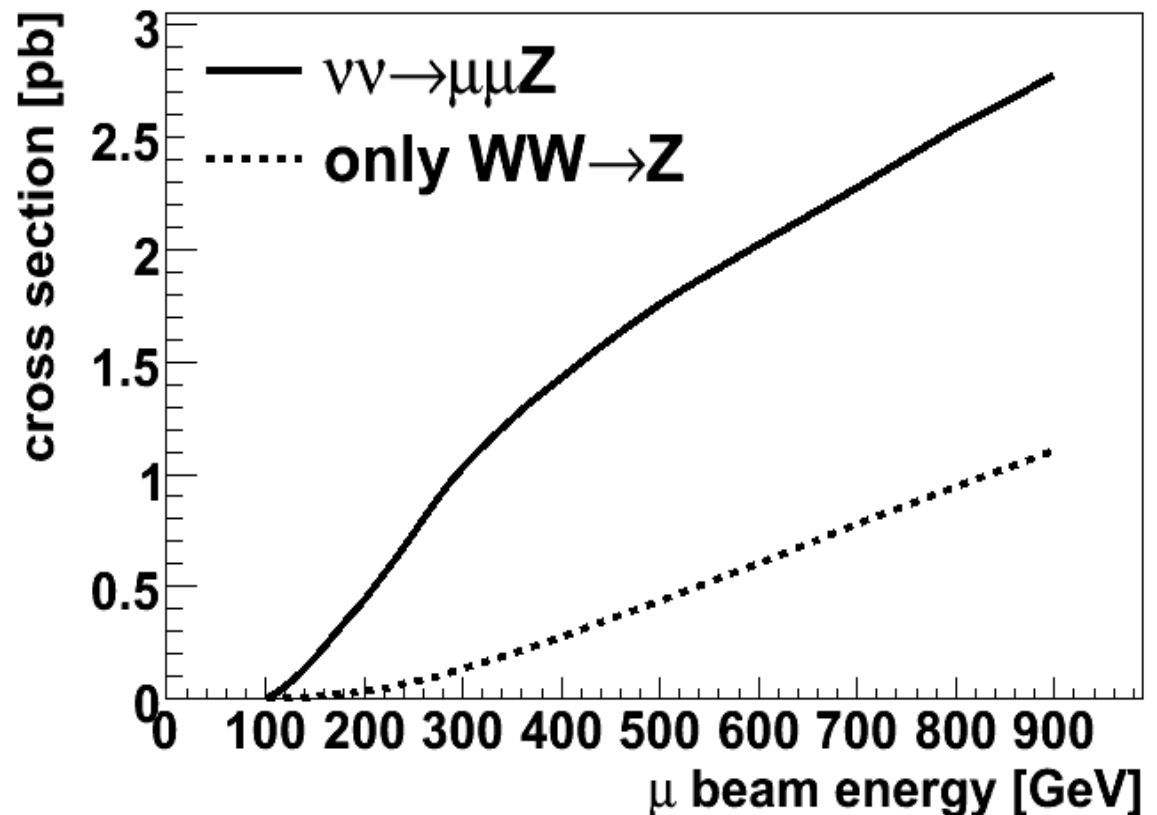
Plus any other new physics
in the neutrino sector
at the TeV scale

Triple gauge boson coupling: WW collider

- Two neutrino beams colliding with each other



- From muon beams:
 $\mu \rightarrow \mu Z$
- Physics background:
 - ZZ production
 - Z from initial state or final state radiation



Unique experimental conditions

- Beam crossing at several Hz, but only few interactions per day
- Beam alignment is a challenge
 - Collision rate too small for immediate feedback
 - Monitor beam profile with small detector
 - Downstream of interaction region
 - monitor alignment continuously
- Large interaction regions
 - Muon storage-ring based neutrino beam diameter $\sim 1\text{ mm}$
 - Proton-beam based neutrino beam diameter $\sim 1\text{ cm}$
 - And plenty of low-energy neutrinos at larger distances

Experimental challenge: backgrounds

- Neutrino interactions with detector material
 - As little detector material as possible in the neutrino path
- At hadron colliders:
 - Neutrino beam is mostly at low energy and divergent
 - Interaction region/detector must be close to neutrino production target
 - Associated muon beams need to be deflected
 - Associated neutrals must not enter interaction region
 - Interaction region must be far away from production target
- At muon storage rings:
 - Associated muon and electron beams

Summary

- Neutrino mass implies the existence of additional particles (right-handed neutrino, ...)
- If these additional particles are light enough, we can produce them directly at neutrino colliders
- Neutrino colliders based on muon storage rings
 - Provide reasonable luminosity already with existing designs
 - Access the highest CM energies in neutrino collisions
- Any muon collider proposal should consider the neutrino collider potential
- Start thinking about the physics potential of high-energy neutrino collisions